Three-Dimensional Models of Core-Collapse Supernova Explosions

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Essential Elements of Neutrino Mechanism

- Pseudo-Chandrasekhar core collapses for hundreds of seconds
- Bounces at nuclear densities and launches a shock wave
- Shock wave stalls due to breakout neutrino losses and photodissociation of accreta within 10's of milliseconds at ~100-150 km into an accretion shock

- Neutrino emission from the inner core (PNS) heats the "gain region" behind the shock, and drives turbulent convection
- Neutrino energy deposition behind the shock and turbulent pressure together eventually overcome the ram pressure of the continuing accretion to launch a supernova
- Delayed Explosion

- Core-collapse supernova explosion is a critical phenomenon/ bifurcation between steady solutions and exploding solutions
- Multi-D (expensive) necessary because most models don't explode (aren't reenergized) in 1D (spherical), but require the extra turbulent pressure/stress of neutrino-driven convection (and other effects)

Core-Collapse Theory: What's New?

- Turbulence crucial to most explosions, necessitating multi-D treatment
- In the last ten years, we could do multiple 2D simulations every year to explore parameters, understand systematics, and explore progenitor structure dependence.
- Techniques improved and computers sped up; resolution-dependence
- Can now do multiple 3D simulations per year (and afford to make a few mistakes!)
- GR, Many-body neutrino-matter corrections (more to do), and PNS convection lead to enhanced ν_μ losses, faster contraction, hence hotter ν_e and anti-ν_e neutrinospheres
- Incorporated inelastic neutrino-matter processes – extra neutrino heating
- Accretion of the Si/O interface; seed perturbations of progenitor (?)

FORNAX: 1D,2D,3D, Multi-Group, Radiation/Hydrodynamics

FORNAX: 1D,2D,3D, Multi-Group, Explicit Radiation/Hydrodynamics

- Solves the Two-Moment Transport Equations, with 2nd and 3rd moment closures (not "ray-by-ray"); second-order accurate in space and time
- Explicit Riemann Godunov-like solution to the Transport operator
- Terms of O(v/c) included in transport; inelastic/redistribution scattering
- Implicit solution to the local transport source terms
- Explicit hydro; full energy and momentum couplings – HLLC
- Conserves energy and momentum to machine precision
- Very good energy conservation with gravity included
- "6"– Dim. = 1(time) + 3(space) + 1(energy-group) + vector Flux
- Logically spherical coordinates – general metric/covariant formulation
- Multipole Gravity (includes GR-like modifications to the monopole)
- Multi-D calculated to the center - Core refinement ("dendritic grid") – improves timestepping by many factors (!); static mesh refinement
- Good strong scaling in core count and scaling in energy group
- Result: Fast multi-D supernova code (by factor of ~5-10 x many other codes)
- Skinner et al. 2016 ; Radice et al. 2017; Burrows et al. 2018; Skinner et al. 2019; Burrows et al. 2019; Vartanyan et al. 2018,2019; Nagakura et al.

FORNAX (cont.)

- Includes: Inelastic scattering off electrons
- Inelastic scattering off nucleons
- Includes in-medium Many-body response corrections (Horowitz et al. 2017)
- General-relativistic monopole gravity correction and gravitational redshifts (can compare with Newtonian)
- Multi-D transport, with rbr+ option (for comparison)
- Weak magnetism and recoil corrections

Fornax Papers

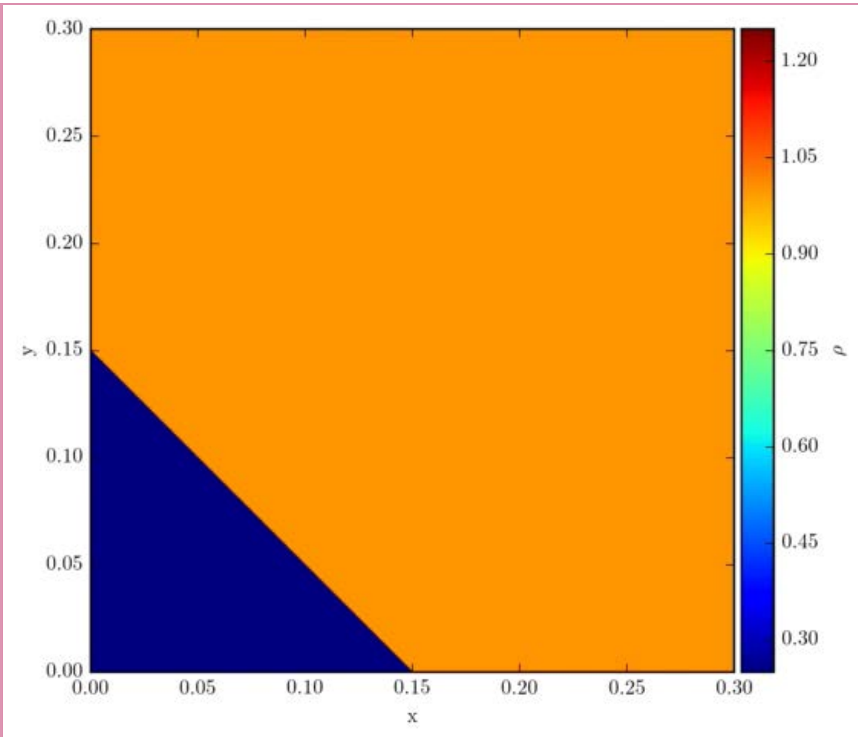
- Wallace et al. 2016 – Neutrino breakout signal
- Skinner et al. 2016 - Ray-by-ray+ study
- Radice et al. 2017 – Electron-capture supernovae
- Burrows et al. 2018 – Crucial component study
- Morozova et al. 2018 – Gravitational wave signal (2D)
- Vartanyan et al. 2018 – “Revival of the fittest”
- Seadrow et al. 2018 – Signals in neutrino detectors
- O’Connor et al. 2018 – 1D code comparison
- Skinner et al. 2019 – Fornax code paper
- Radice et al. 2019 – Gravitational waves (3D)
- Vartanyan et al. 2019 – 3D explosion model
- Burrows et al. 2019 – Multiple low-mass 3D explosion models
- Nagakura et al. 2019 – 3D model Resolution study

Recent 3D Fornax Simulations with Necessary Realism

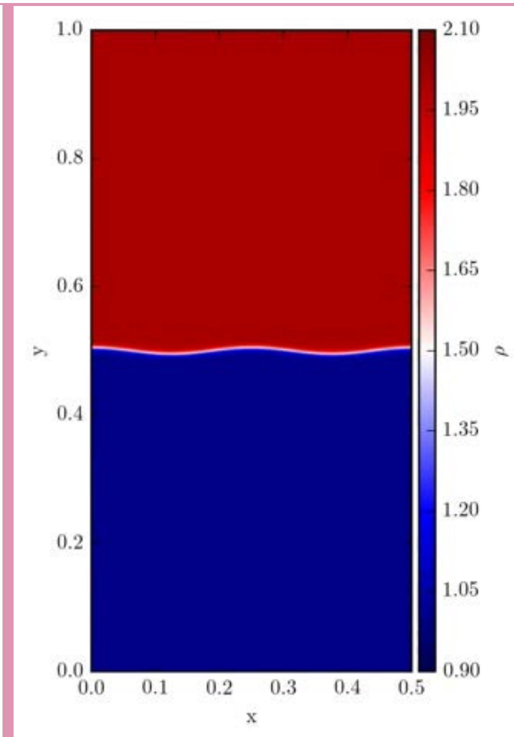
- 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 25 solar mass models (default physics and resolution)
- 19 solar mass model: low, medium, high angular resolution; with and without Horowitz correction; monopole versus multipole

- Default resolution: 678 x 128 x 256; 12 energy groups; dendritic grid

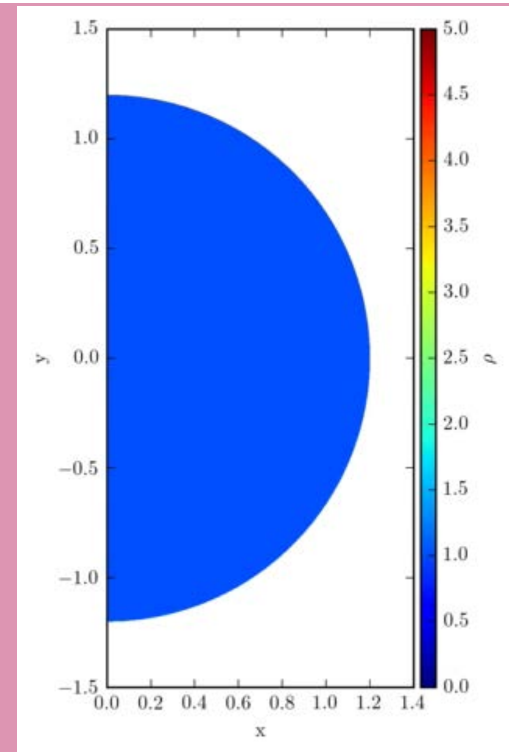
(~50 2D models performed: 678 x 128)



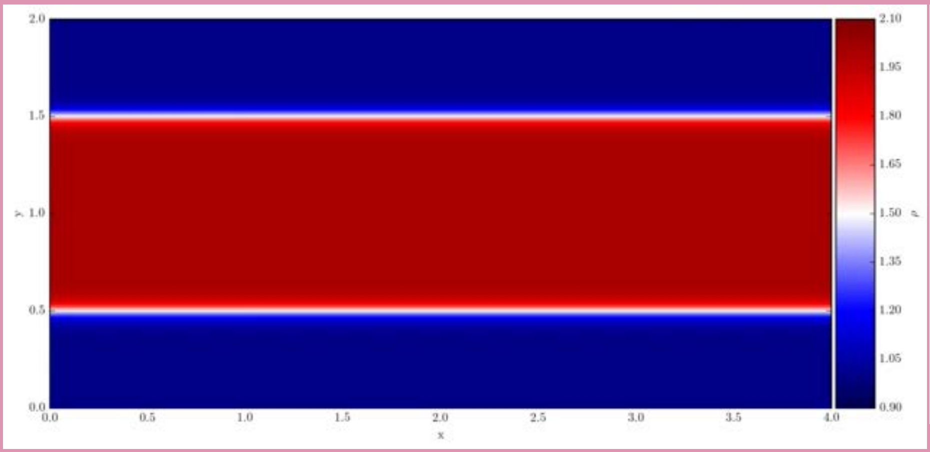
0.30
0.25
0.20
0.15
0.10
0.05
0.00
y
0.00
0.05
0.10
0.15
0.20
0.25
0.30
x
1.20
1.05
0.90
0.75
0.60
0.45
0.30
ρ



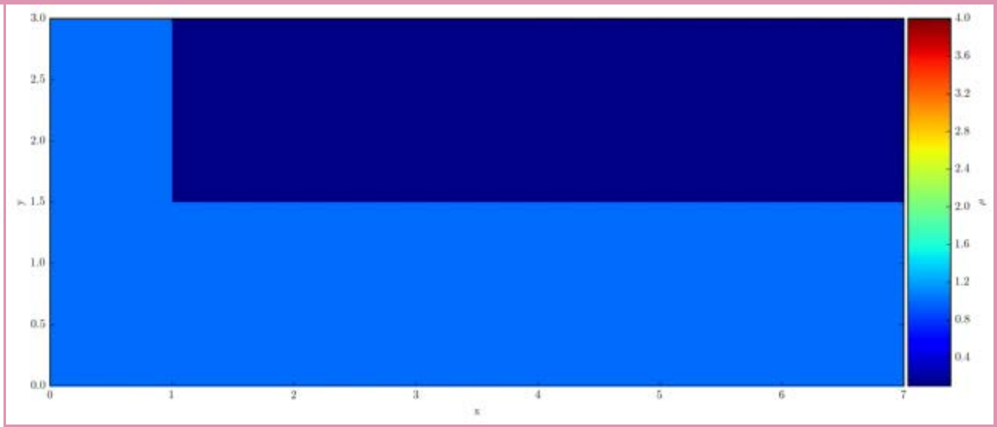
1.0
0.8
0.6
0.4
0.2
0.0
y
0.0
0.1
0.2
0.3
0.4
0.5
x
2.10
1.95
1.80
1.65
1.50
1.35
1.20
1.05
0.90
ρ



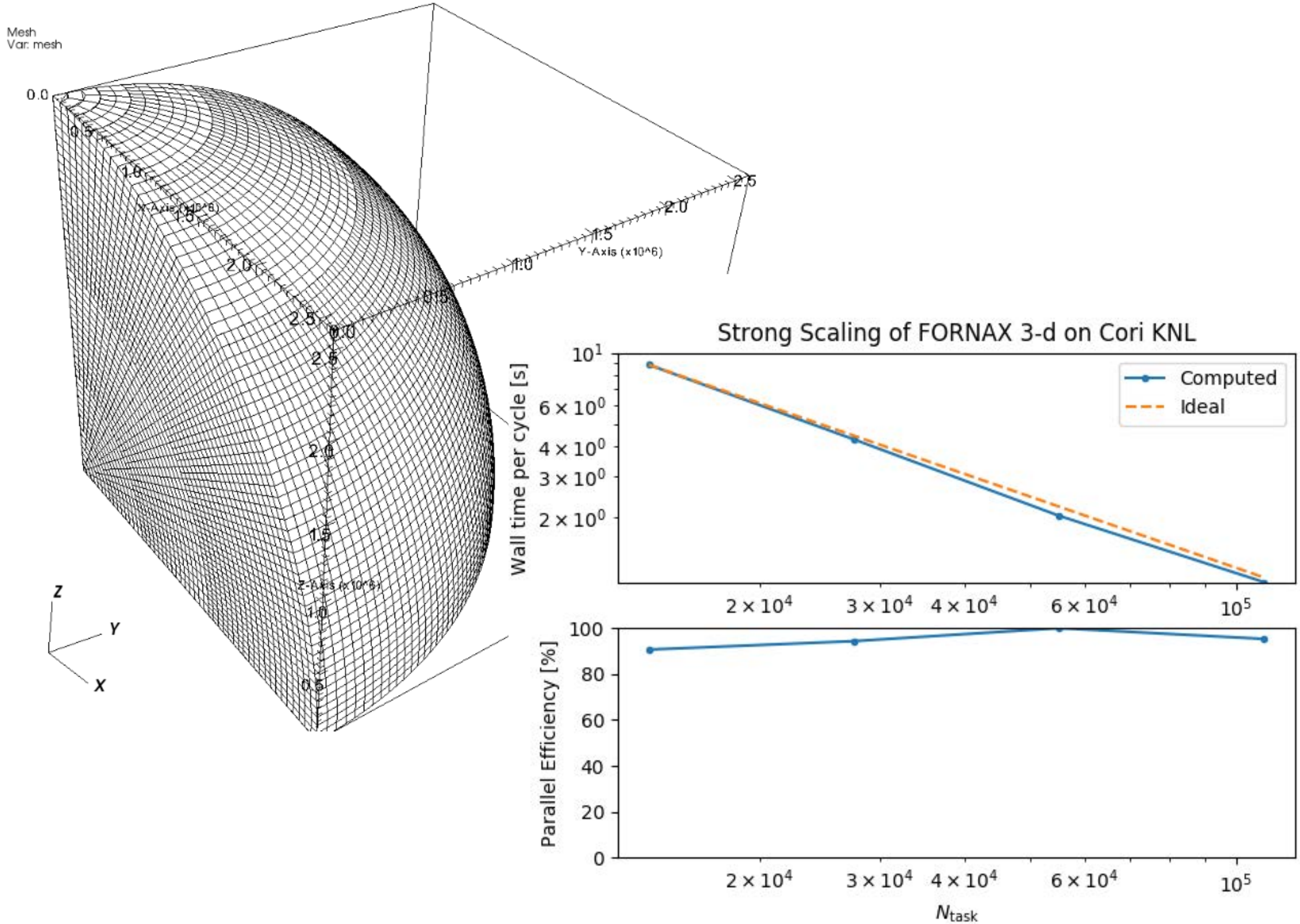
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
x
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ρ



2.0
1.5
1.0
0.5
0.0
y
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
x
2.10
1.95
1.80
1.65
1.50
1.35
1.20
1.05
0.90
ρ



3.0
2.5
2.0
1.5
1.0
0.5
0.0
y
0
1
2
3
4
5
6
7
x
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
ρ

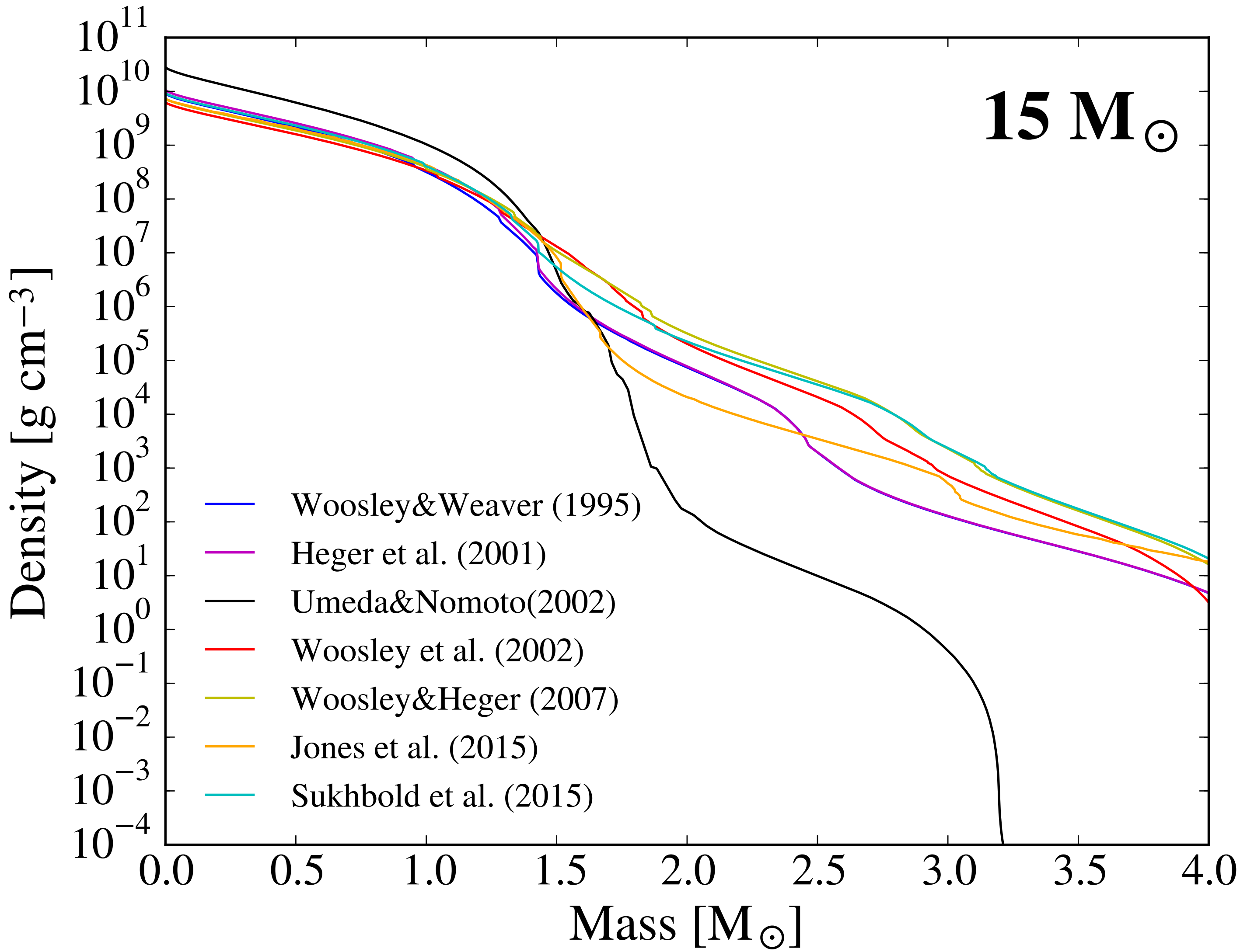


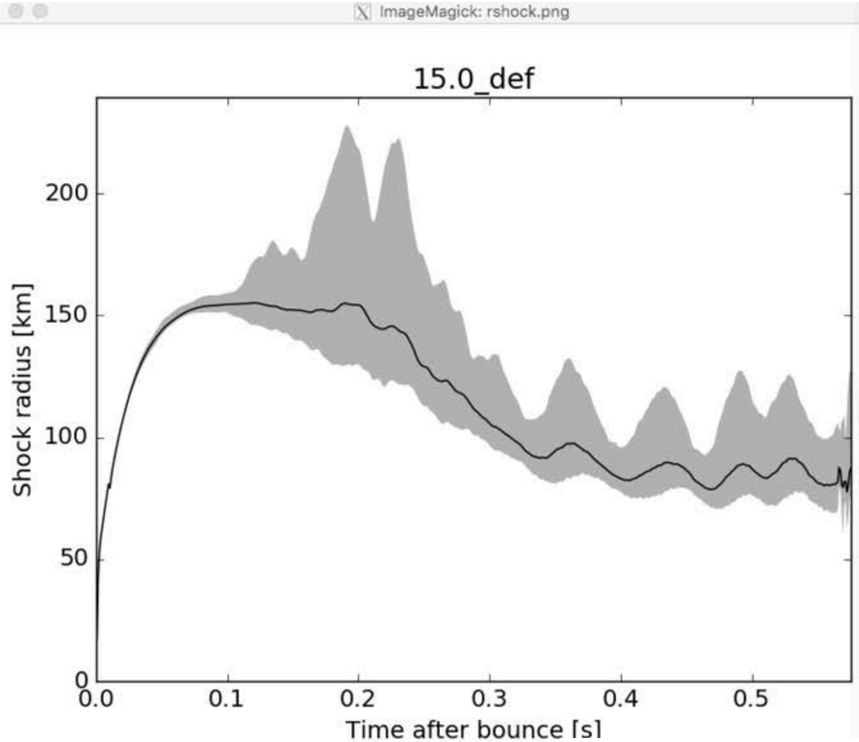
Mesh
Var: mesh
X-Axis (x10^6)
Y-Axis (x10^6)
Z-Axis (x10^6)
Z
Y
X
Strong Scaling of FORNAX 3-d on Cori KNL
Wall time per cycle [s]
Computed
Ideal
Parallel Efficiency [%]
$N_{\rm task}$

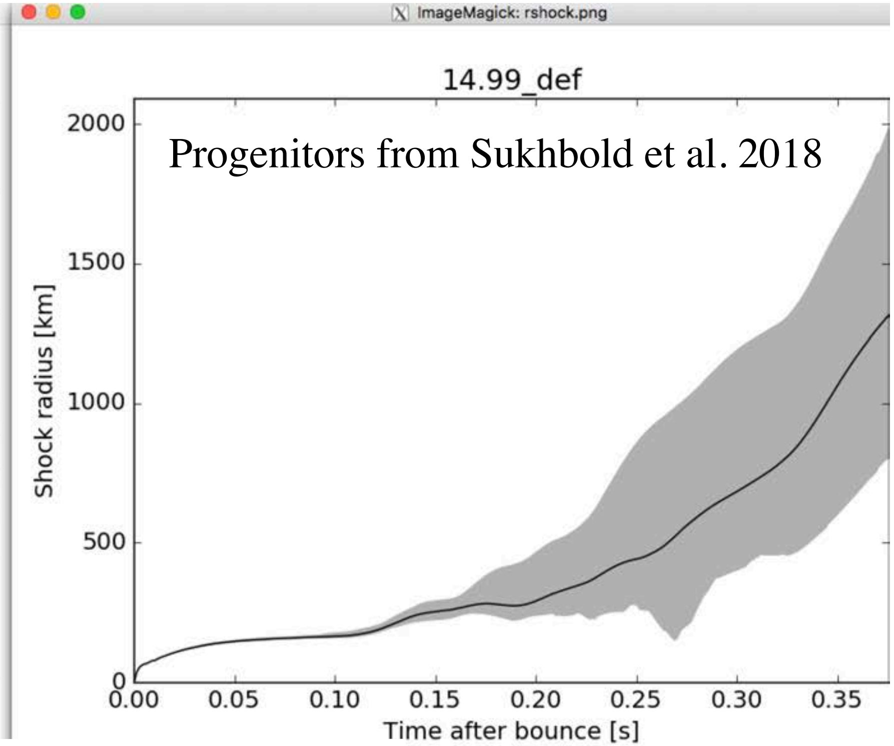
Important Roles of Progenitor Models:

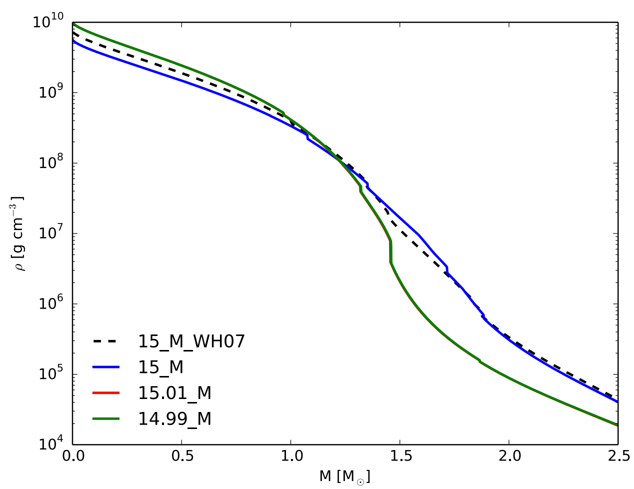
Density Structures, Rotational Profiles, Seed Perturbations

Different Groups, Same ZAMS Mass





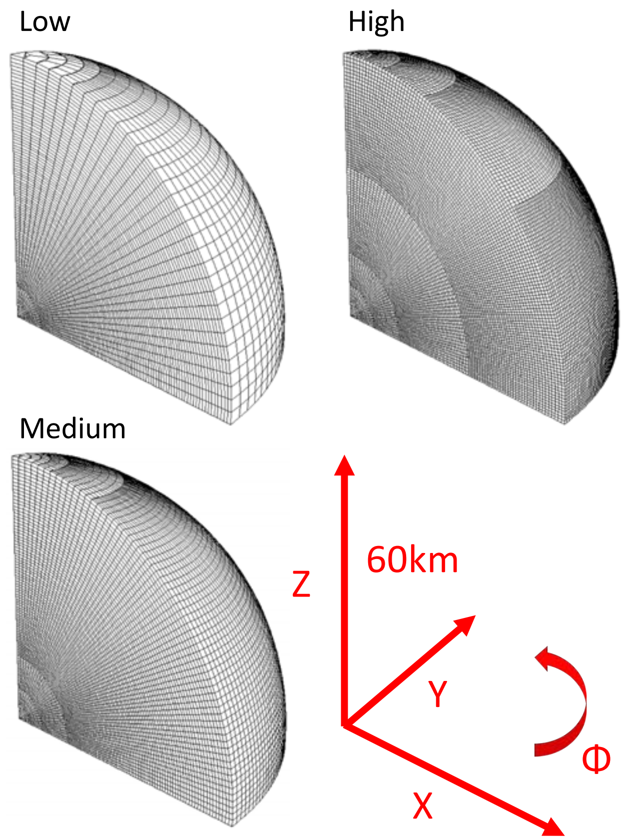


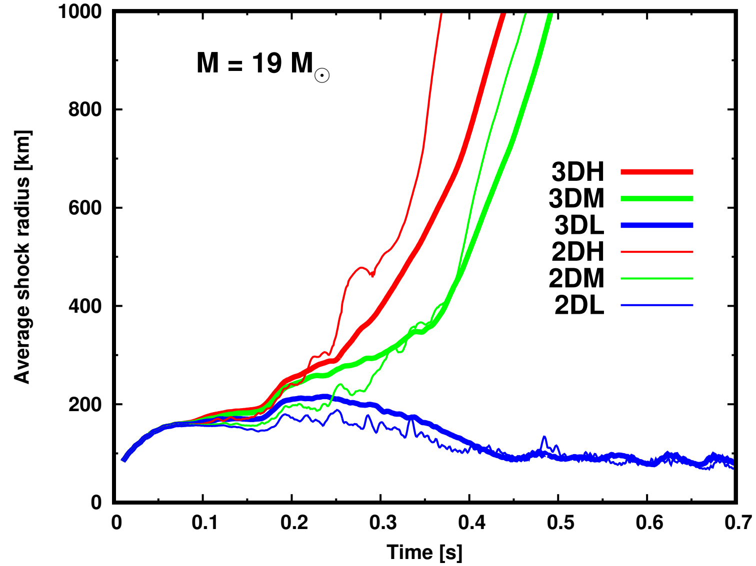


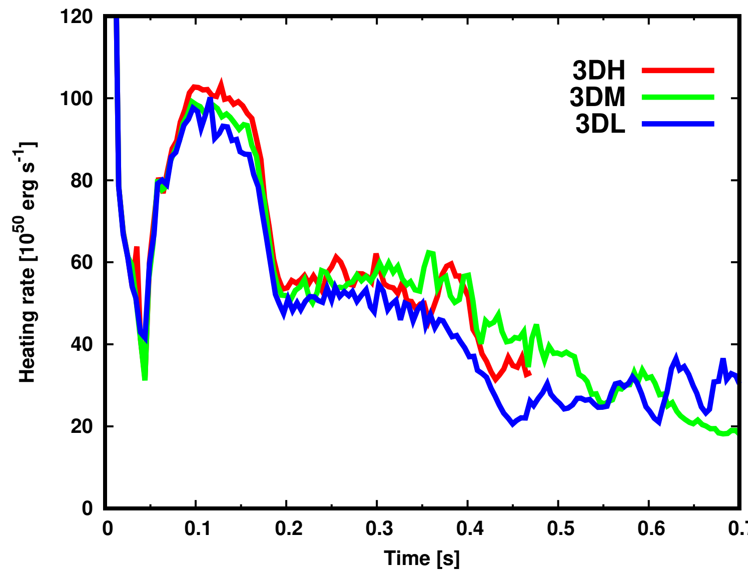
Vartanyan, Burrows, et al. 2018b

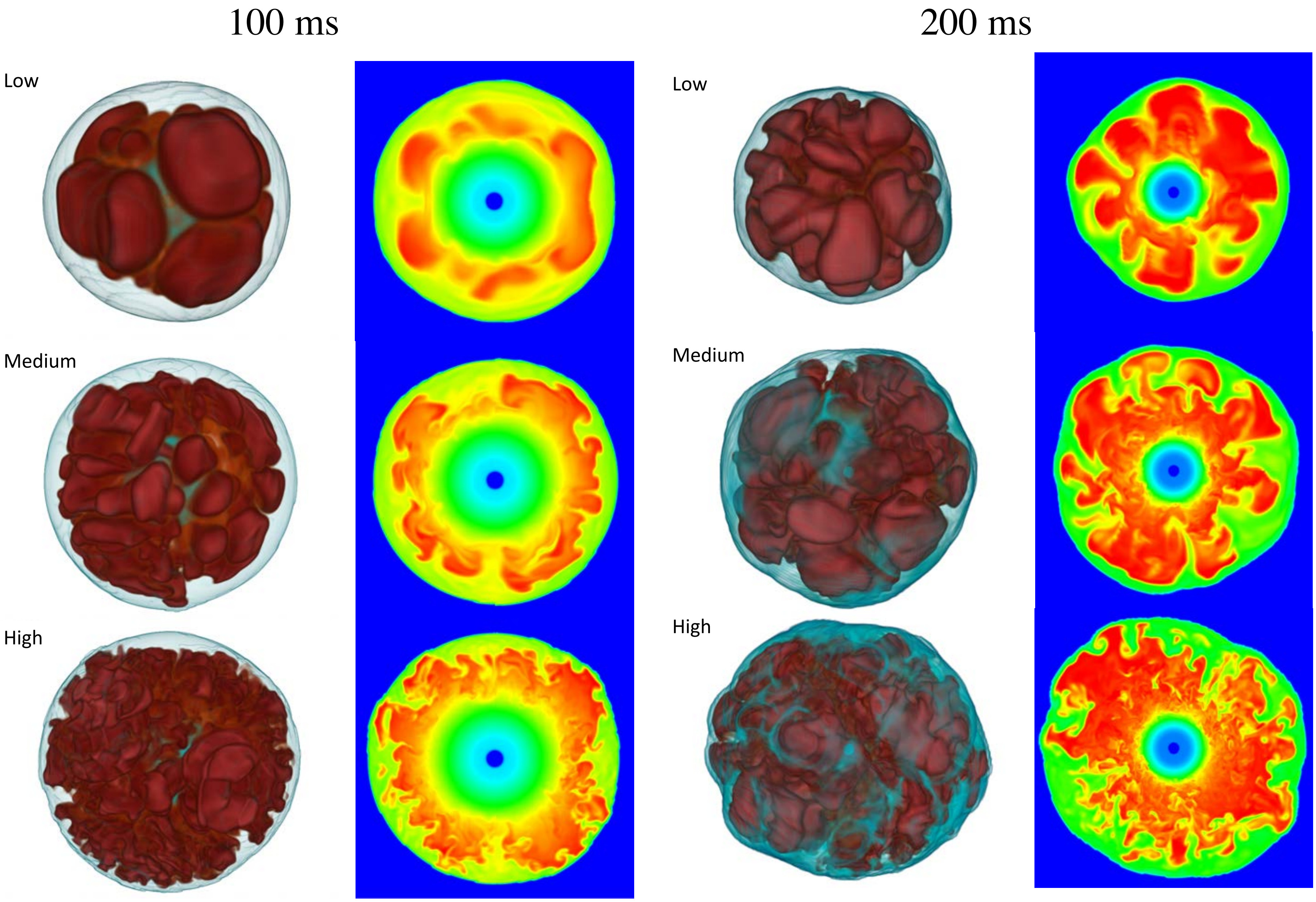
Spatial Resolution Dependence

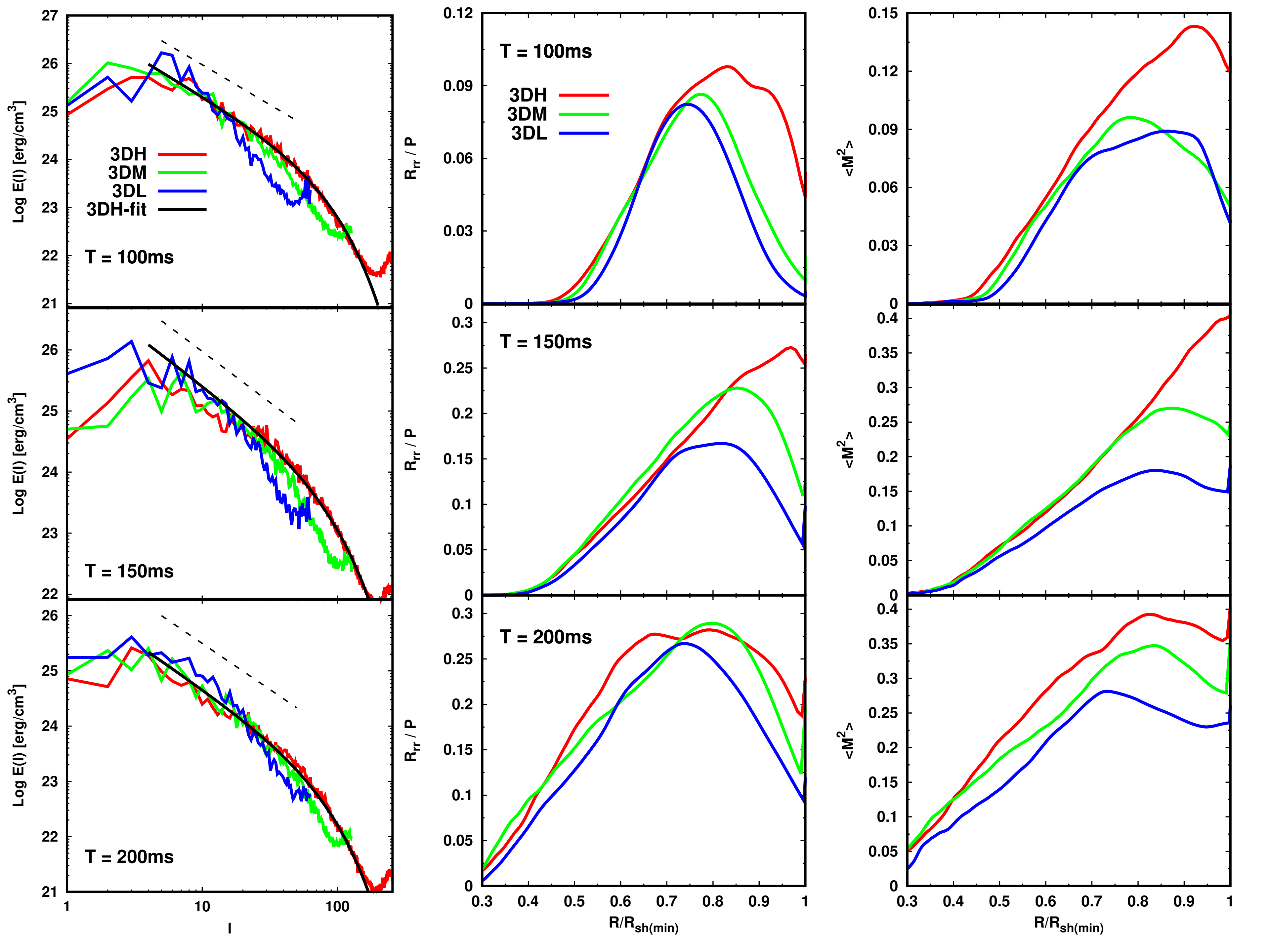
Nagakura et al. 2019


Low
High
Medium
Z
60km
Y
X
Φ


M = 19 M$_\odot$
3DH
3DM
3DL
2DH
2DM
2DL
Average shock radius [km]
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time [s]


3DH
3DM
3DL
Heating rate [10^{50} erg s^{-1}]
120
100
80
60
40
20
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time [s]


100 ms
200 ms
Low
Medium
High
Low
Medium
High



Log E(l) [erg/cm^3]
l
3DH
3DM
3DL
3DH-fit
T = 100ms
T = 150ms
T = 200ms
R_{rr} / P
$\langle M^2 \rangle$
R/$R_{sh(min)}$

New Fornax 3D Simulations

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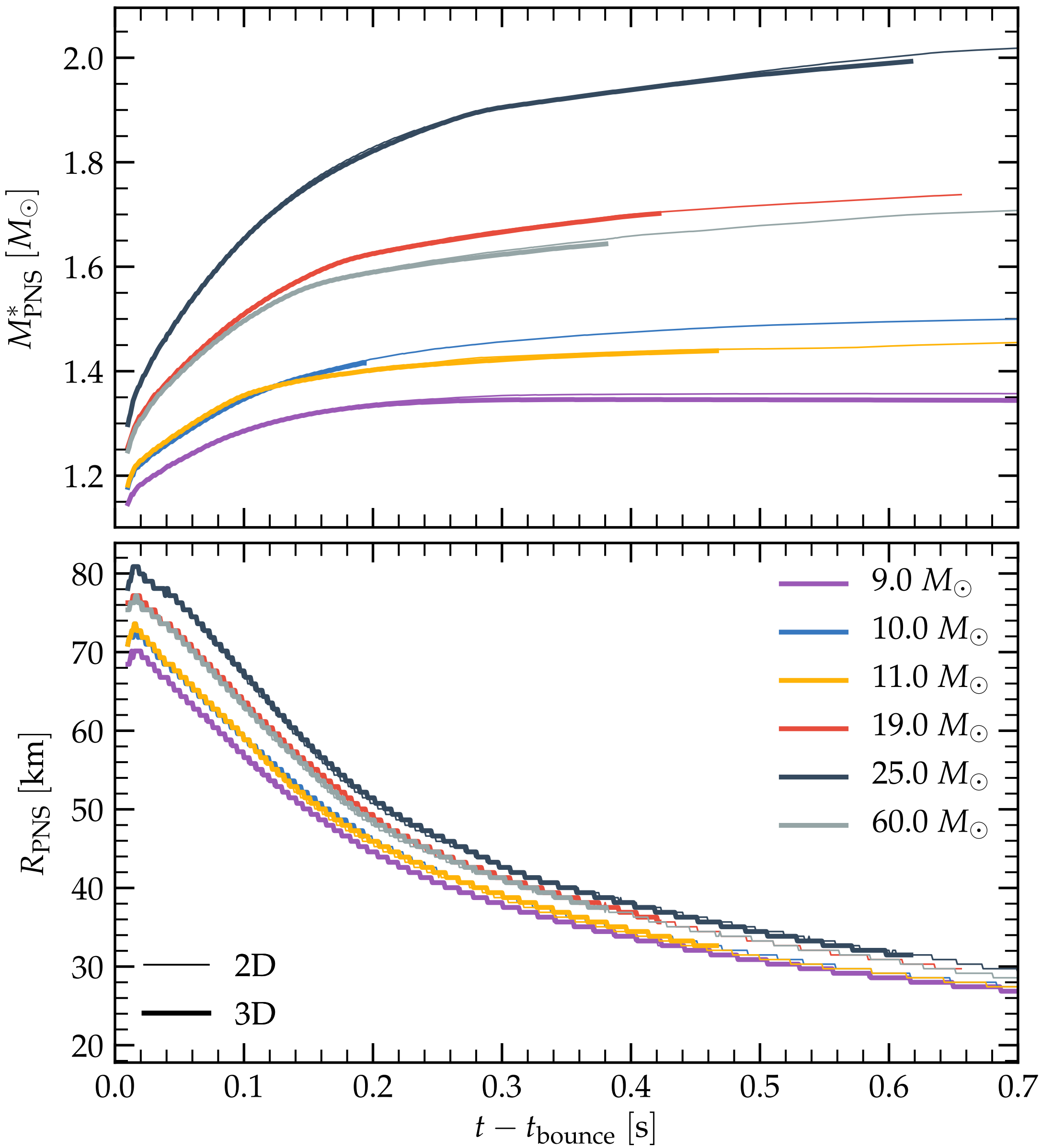
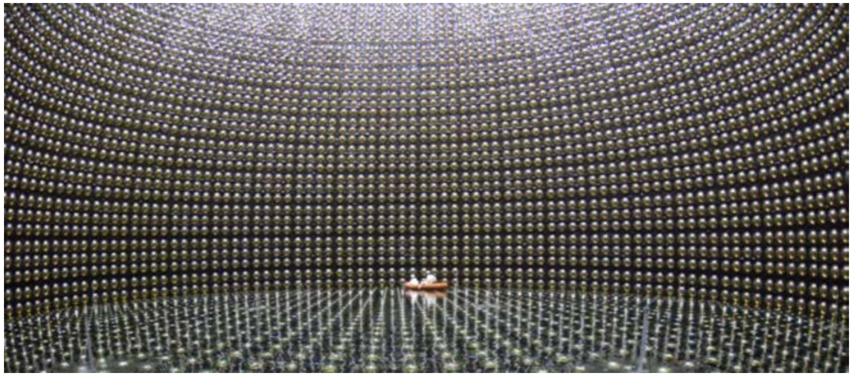


2.0
1.8
1.6
1.4
1.2
$M^*_{\mathrm{PNS}}\ [M_\odot]$
80
70
60
50
40
30
20
R_{PNS} [km]
9.0 $M_\odot$
10.0 $M_\odot$
11.0 $M_\odot$
19.0 $M_\odot$
25.0 $M_\odot$
60.0 $M_\odot$
2D
3D
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
$t - t_{\mathrm{bounce}}$ [s]

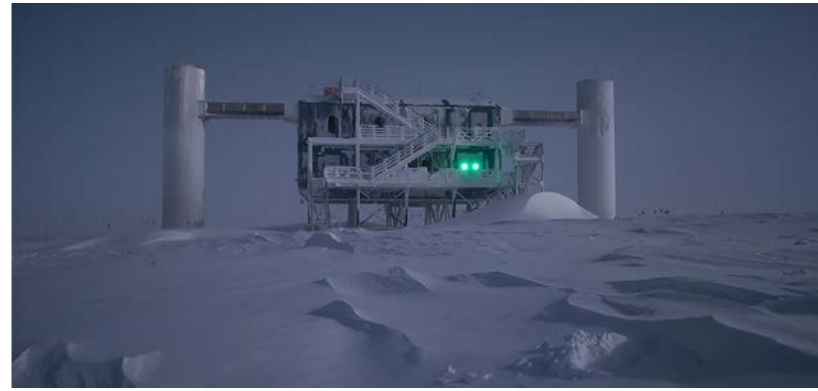
Supernova Neutrino Detection

SUPERK, HYPERK, DUNE, JUNO, ICE CUBE

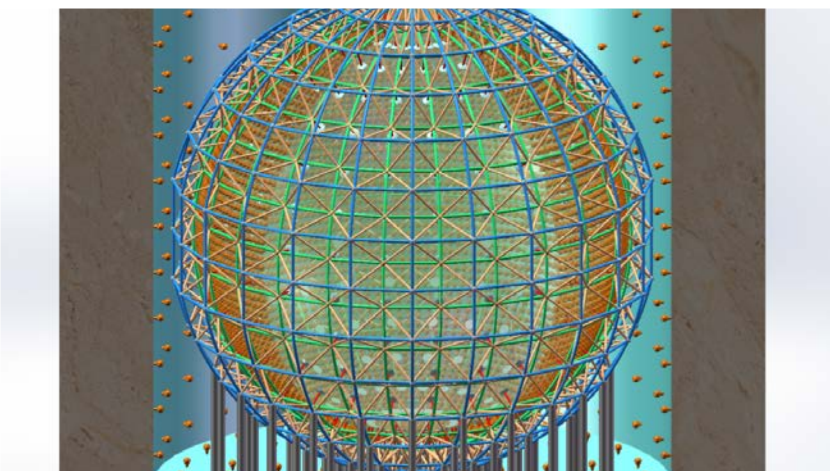
SN Neutrino Observatories



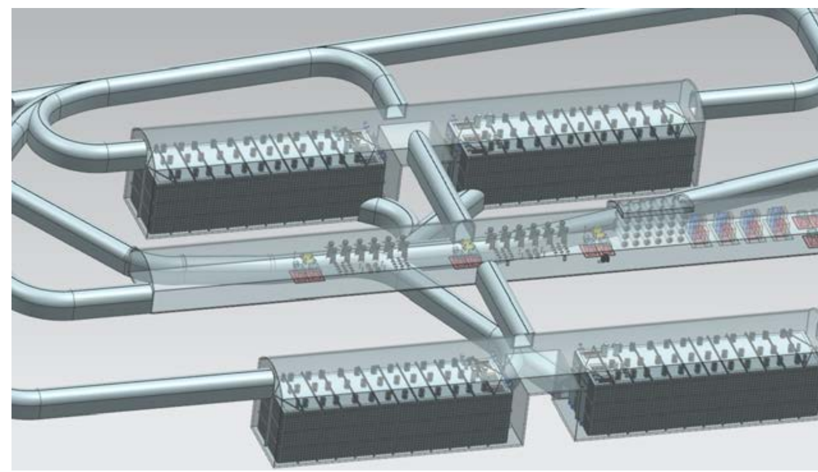
Super-Kamiokande
(Water Cherenkov)



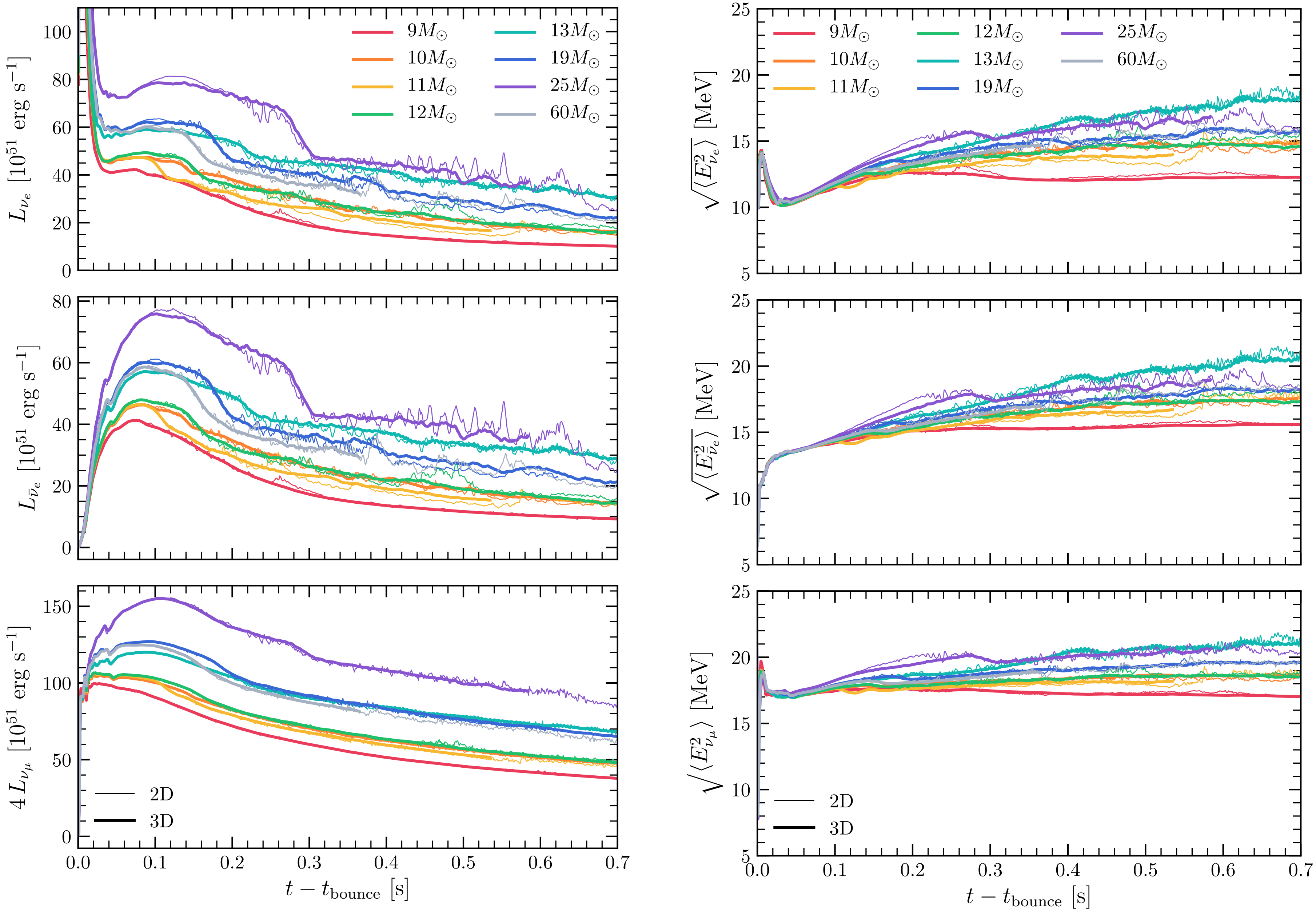
ICECUBE
(Longstring Ice)



JUNO
(Hydrocarbon Scintillator)



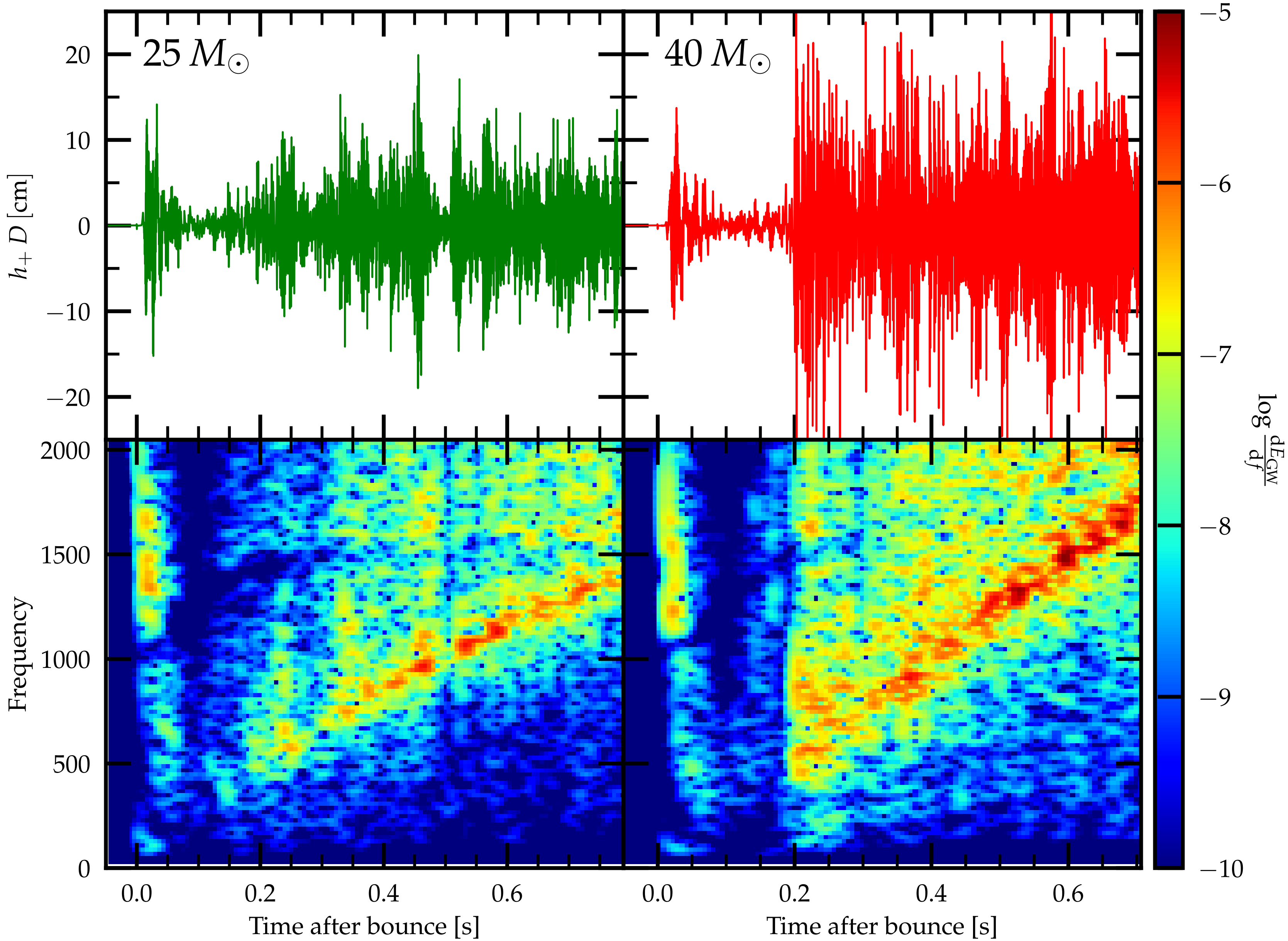
DUNE
(Liquid Argon TPC)



L_{ν_e} $[10^{51}$ erg s$^{-1}]$
$L_{\bar{\nu}_e}$ $[10^{51}$ erg s$^{-1}]$
$4\,L_{\nu_\mu}$ $[10^{51}$ erg s$^{-1}]$
$\sqrt{\langle E^2_{\nu_e}\rangle}$ [MeV]
$\sqrt{\langle E^2_{\bar{\nu}_e}\rangle}$ [MeV]
$\sqrt{\langle E^2_{\nu_\mu}\rangle}$ [MeV]
$t - t_{\rm bounce}$ [s]
$9M_\odot$
$10M_\odot$
$11M_\odot$
$12M_\odot$
$13M_\odot$
$19M_\odot$
$25M_\odot$
$60M_\odot$
2D
3D

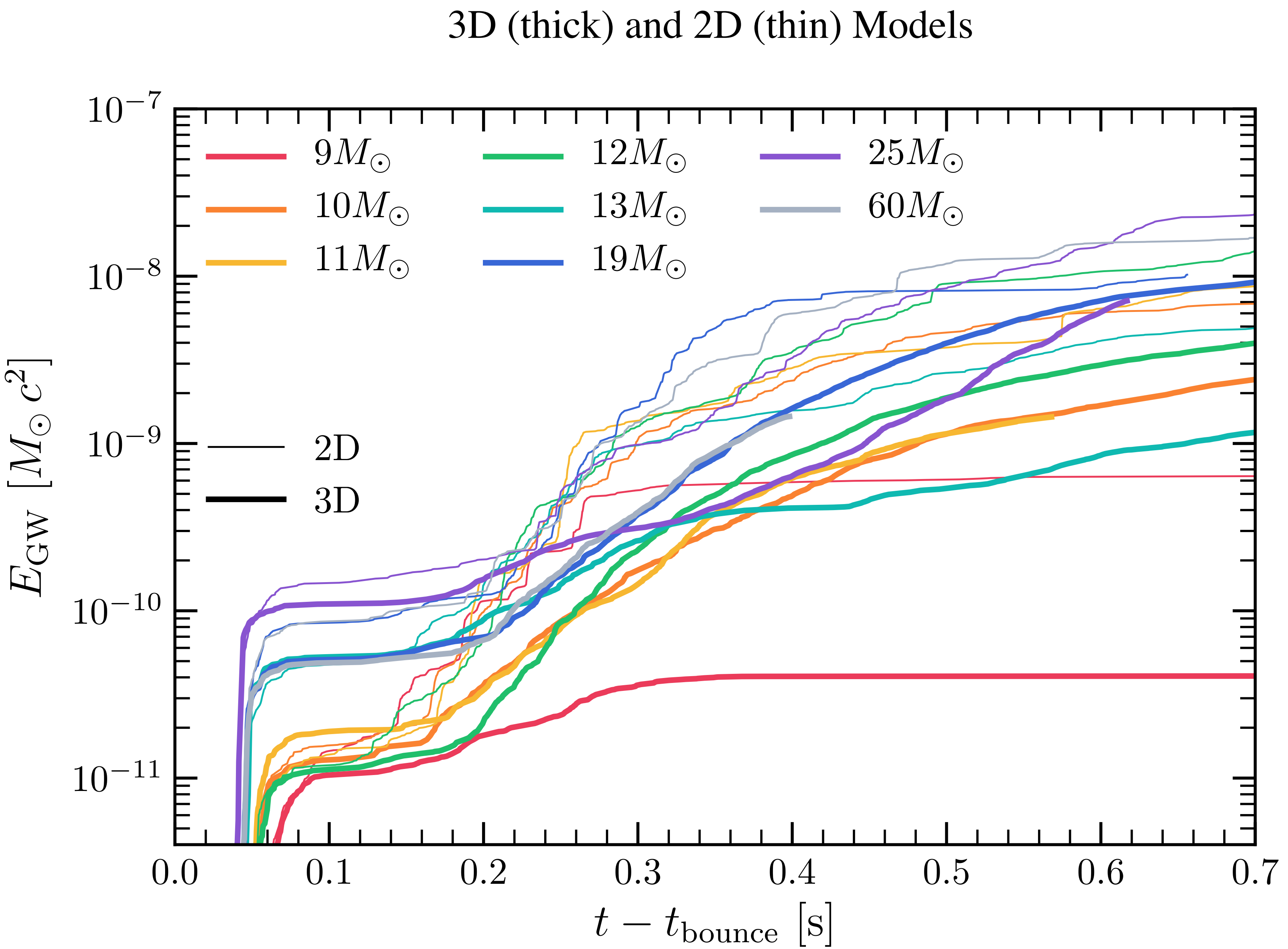
Gravitational Radiation Signals from Core-Collapse Supernovae

Radice, Morozova, Burrows, Vartanyan et al.
2018-2019

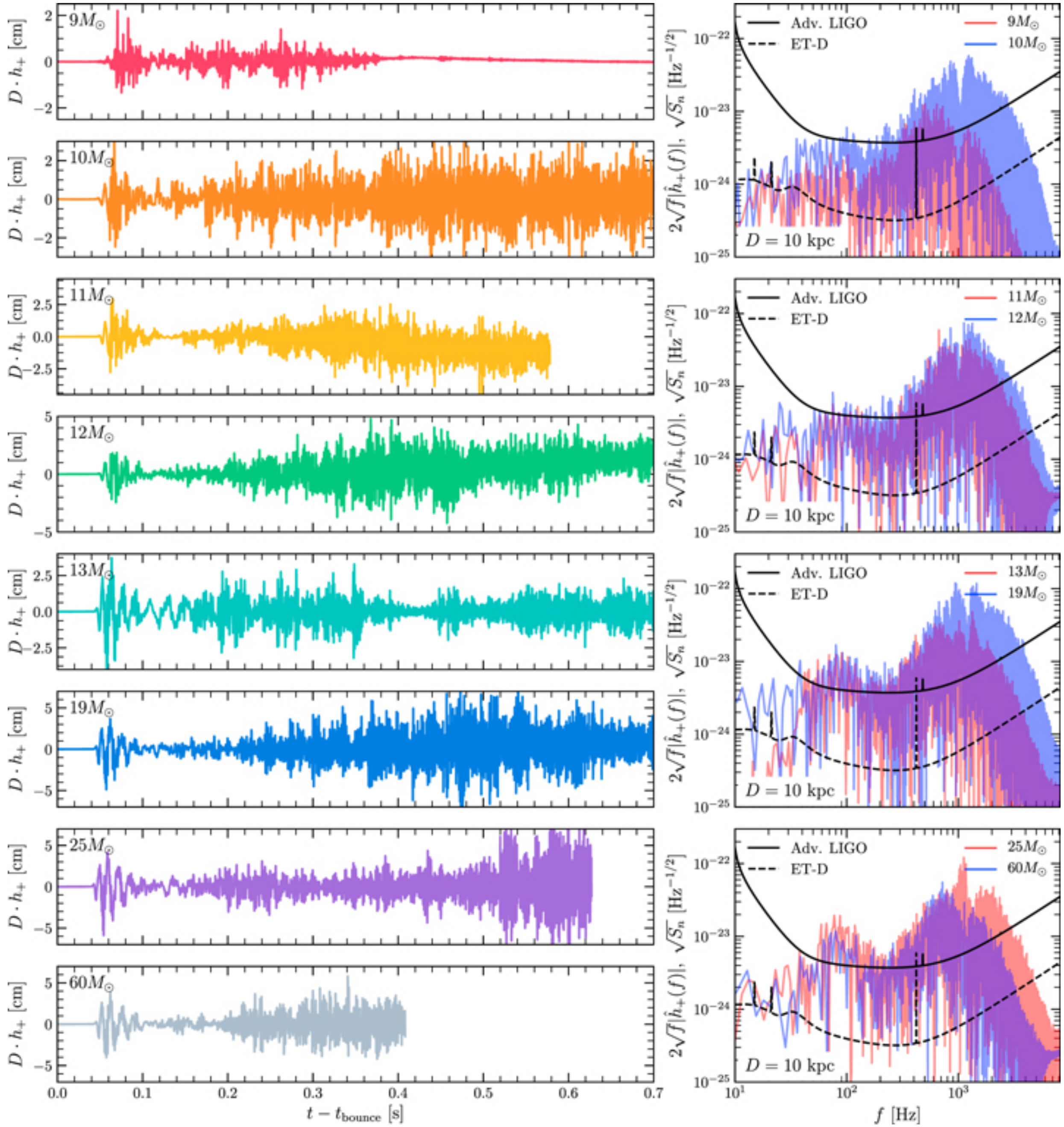


25 $M_\odot$
40 $M_\odot$
$h_+ D$ [cm]
Frequency
Time after bounce [s]
Time after bounce [s]
$\log \frac{dE_{GW}}{df}$





3D (thick) and 2D (thin) Models
$9M_\odot$
$10M_\odot$
$11M_\odot$
$12M_\odot$
$13M_\odot$
$19M_\odot$
$25M_\odot$
$60M_\odot$
2D
3D
$E_{\rm GW}$ $[M_\odot\, c^2]$
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$t - t_{\rm bounce}$ [s]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Radice et al. 2019



Core-Collapse Theory: A Status Summary

- Can now perform many 3D simulations per year on HPC resources such as Blue
- Waters!
- Proximity to critical explosion curve amplifies effects of sub-dominant processes, etc.
- Can explain current differences between groups (!?)

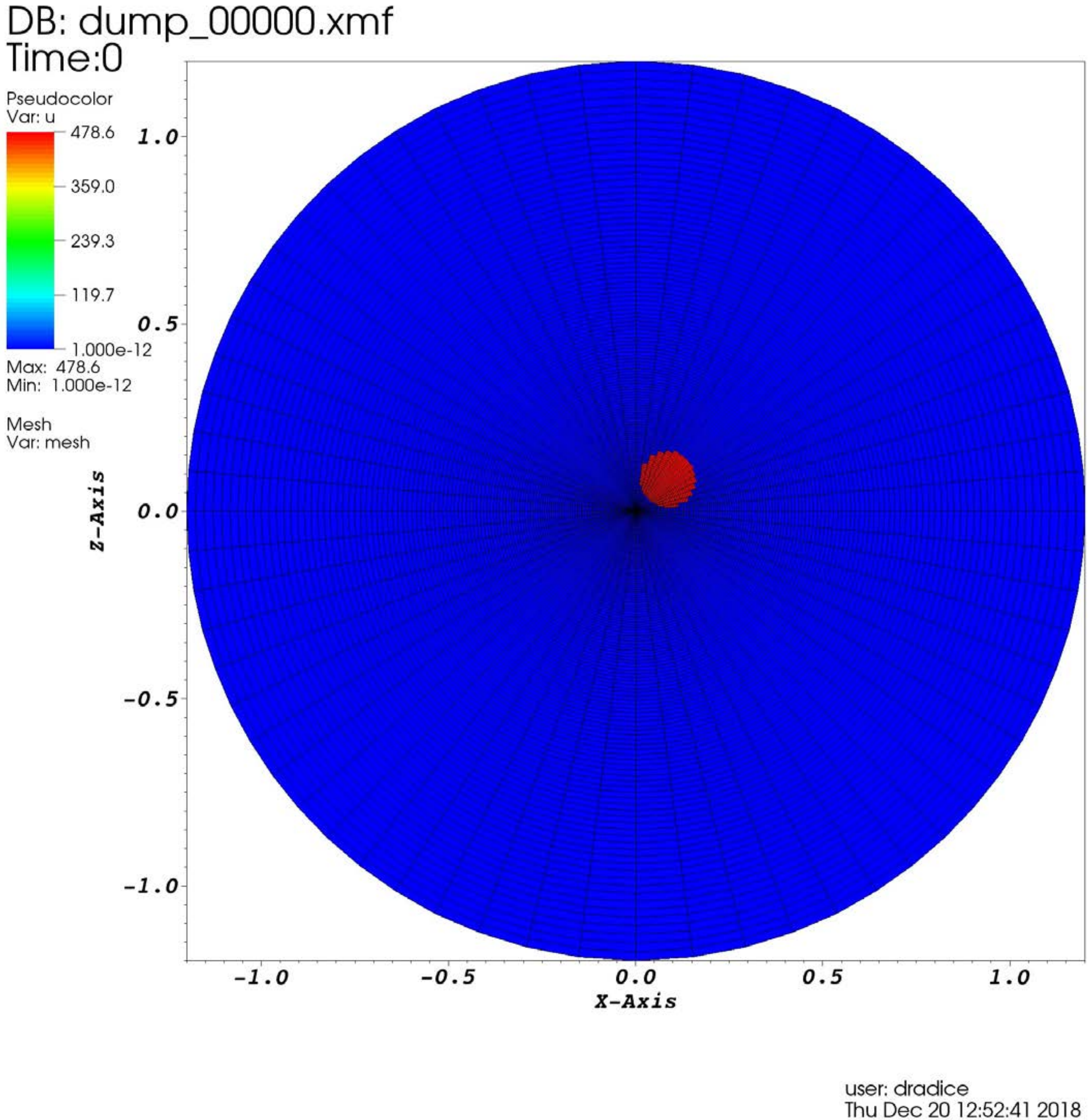
- Turbulent convection is Key Enabler of explosion for (almost) all viable mechanisms; turbulent stress, simultaneous accretion and explosion
- Neutrino-driven convection > SASI (when object explodes to yield SN)
- SASI is not a mechanism – can't generate much entropy; failed models show SASI (spiral modes)
- Accretion of the Si/O interface
- 3D different from 2D (turbulent pressure, spectrum; scales)!

- Various heating processes (in-medium/many-body, inelastic on electrons, inelastic on nucleons) add "non-linearly"
- Structure factor/many-body corrections! Neutrino-matter interactions!

- Proto-neutron Star (PNS) Convection - boosts ν_μ neutrino luminosity
- Seed Perturbations

- Progenitor profiles/structure important! (e.g., Meakin & Arnett; Couch et al. 2015; B. Muller et al. 2016); Seed Perturbations, Density profiles, Si/O shelfs?
- Rotation!?
- Crucial role for microphysics – many-body/structure-factor corrections, inelastic scattering; when near critical curve, small effects are amplified – (partial) origin of differences between groups

Fornax: 3D Off-Center Sedov Blast Wave



16 solar mass

Time = 0.677 s